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RESEARCH ARTICLE

Hybrid battery-supercapacitor storage for an electric forklift: a life-cycle cost assessment

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Abstract Supercapacitors, more properly named electrochemical capacitors (EC), have a great potential in constituting the premium power reserve in a variety of energy- and power-intensive applications in transport and in electricity grids. EC may be used in conjunction with electrochemical storage systems, such as the batteries of various chemistries (lead-acid, sodium-nickel chloride or sodium-sulphur, nickel-metal hydride and even lithium-based systems), in a hybrid configuration where the functions of energy and power can be conveniently separated between the two storage devices and then optimized. Recently, an electric forklift has been commercialized with such a hybrid storage system, without any demonstrated specification of the advantages achievable with this configuration. In this article, the effective technical and economical benefits of this EC integration are theoretically and experimentally evaluated, by means of a conventional electric forklift. The reference vehicle drivetrain is modified by combining a conventional traction lead-acid battery, already used in the vehicle, and a commercial EC. The performances of the modified electric forklift are simulated with already developed vehicle and components models and validated with experimental data. Simulations and electrical tests confirm the functional relationship, expressed in exponential form, between battery lifetime and peak current and demonstrate the technical and economical potentialities of the use of these hybrid configurations, such as the increased efficiency and the prolonged battery life (more than doubling the life of the battery without EC), due to the reduced battery operating stress, and an economical saving (about 30 %), able to compensate initial extra-costs for vehicle modification and battery replacement.

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1 Introduction and background

Supercapacitors, also named electrochemical capacitors (EC), ultracapacitors and electric double-layer capacitors (EDLC), due to their capability to deliver high specific power during few seconds or more, are presently considered as one of the most promising electric storage devices in a variety of applications in transport and in electricity grids.

The potential advantages of such high power and long lasting storage devices have been under investigation at ENEA (Italian National Agency for new technologies, energy and economic sustainable development) in the last two decades, by starting from a technological survey at the end of the 80s, and subsequently participating in various European and national projects with promising scientific and technological results on materials and cells designs. In this long period, ENEA have been studying commercial and novel ECs, from prototype cells up to commercial products, in a purpose-developed test facility and electrochemical research laboratories. More recently, focus was put on application-oriented activities, by covering a wide range of EC uses, such as passenger cars with electric traction, levelling of electrical loads, UPS (Uninterruptable Power Systems), and electric drives for elevators and load lifting [1–4].

One of the most interesting applications of EC is in hybrid systems, which couple the EC with electrochemical storage systems, such as batteries of various chemistries (lead-acid, sodium-nickel chloride or sodium-sulphur, nickel-metal hydride and even lithium-based). In this configuration, the battery stores the energy and slowly charges the EC, which acts as power storage and then supplies the peak power loads of the hybrid system. The EC could also level the load from intermittent or regenerative power recovery systems. In this way, the EC could extend the power load the battery could support and extend the battery's lifetime by reducing the number and the depth of charge/discharge cycles. Such a hybrid system is able to use the best performance of each storage technology.

Various mobile and stationary applications of this hybrid configuration have been analysed and modelled in the last 15 years to clearly identify its technical and economical potentialities. Particularly in battery-powered, hybrid and fuel cells vehicles, the key features and benefits have been modelled and experimentally investigated with the comparison of different configurations (with or without one or more DC/DC converters), showing positive impacts of the hybrid configuration in improving the overall energy efficiency and power performance, while protecting the battery from operating stress [5–16].

While previous research activities have produced a great deal of general information about possible effects and impact of various hybrid configurations, they have not considered the application in electric forklift with a combined analysis and evaluation, through simulation studies and experimental validation, of technical and economical benefits. In this specific application, the use of composed (hybrid) battery-EC storage systems is able to improve performances (availability, durability, range, and much more) of the electric forklift, as already proposed by Komatsu in its commercial ARION electric forklifts. In fact, the EC addition is able to extend the operation time not only by improving the energy efficiency (thanks to a higher contribution of regenerative braking), but also by reducing the battery power requirement at higher discharge rates.

This article describes the optimization process for the integration of battery with supercapacitors, which is based on the combination of a conventional lead-acid battery with a commercial EC of EDLC-type and on the real operating conditions of the traction system and of the current pulses delivered by the EC bank. Simulation studies on the benefits of adding EC to the existing lead-acid batteries are conducted by adapting already developed models for the forklift, and the main components, operating with a conventional and an experimental driving profile, supplied by the reference vehicle manufacturer. Experimental data are used for validating the simulation results and also for a techno-economic analysis of the proposed hybrid storage system to assess life-cycle costs and convenience with respect to a conventional storage system.

Fig. 1 Commercial CESAB B416 electric forklift, used as reference vehicle

The analysis is supported by the results of life-cycle tests carried out in the ENEA laboratories, in the framework of a national program funded by the Italian Ministry of Economic Development. The tests confirm that the mathematical functional relationship between battery life and requested current peaks better fitting these data is of exponential form, as proposed in [18].

In conclusions, this article summarizes both simulation and experimental work suitable for assessing optimal design and technical specifications of the hybrid storage system in a commercial electric forklift. The research activities take into account real operating conditions and economic suitability.

The first part presents the adapted model application and the reference case study by summarising the main simulation results, carried out in MATLAB/SIMULINK environment. The second part regards the experimental activities with the description of the main test results used for model validation and design optimization. Finally, the last part reports the main conclusions of the economic assessment with the summary of the expected savings achievable over the life of the forklift by converting the conventional storage system in a hybrid configuration with EC integration.

2 The forklift case study and the model

The choice of an electric forklift for the application of hybrid battery-EC storage systems has been motivated by the availability of experimental data and preliminary studies on lead-acid batteries [16–21] and on the

Table 1 Technical characteristics of the CESAB B416 electric forklift

Characteristics	Value
Maximum payload, kg	1,600
Battery capacity, Ah	525–625
Battery voltage, V	48
Load centre, mm	500
Lift height, mm	2,970
Travel speed, km/h	19
Lifting Speed with/without load, m/s	0.4/0.6
Turning radius, mm	1,719

introduction on the market of a commercial electric forklift with a hybrid storage system.

The simulation and experimental activities have been carried out on a reference electric forklift, CESAB B416, reported in Fig. 1.

The main technical specifications of the reference electric forklift are reported in Table 1.

The battery system is composed of 24 series-connected lead acid cells with a capacity of 575 Ah. This type of battery system does not include any battery management system, because it was considered not necessary for the specific application.

In addition to the plate data of the reference vehicle, the manufacturer also supplied the experimental profile of the electrical power (exchanged by the battery) during a typical mission of such a forklift, which is used as input data of the developed model (Fig. 2).

Such typical mission is composed of different functions: motion of the forklift, lifts up and down, and stops. Positive and negative values of power are recorded, because the forklift has also the regenerative function, able to partially recharge the battery during braking. The overall energy consumption amounts to 4.4 kWh per working hour. At the end of this cycle, a rest period of 40 s is included.

2.1 Model and simulations

To analyse the behaviour of the hybrid storage system, a complete vehicle model has been developed using MATLAB/SIMULINK software. The descriptions of the battery model and the complete vehicle model are reported, respectively, in [19] and [20]; the lead acid battery model takes into account the variation of the capacity with the discharge current, and the electrical equivalent circuit of the battery is a simple electromotive force in series with a resistance, as described in [19]. Both the resistance and the electromotive force are dependent on the state of charge (SOC) of the battery.

The battery module used for the simulation is the VRLA (Valve Regulated) lead-acid Tudor 5H-445 model. Table 2 reports the battery capacity in function of different discharge currents. The equation used to calculate the capacity at various discharge currents, and also the temperature is reported below [19]:

$$C = C(I,t) = \frac{K_C \times C_0}{1 + (K_C - 1) \times \left(\frac{I}{I^*}\right)^{\delta}} \times \left(1 + \frac{\theta}{-\theta_f}\right)^{\varepsilon} \qquad (1)$$

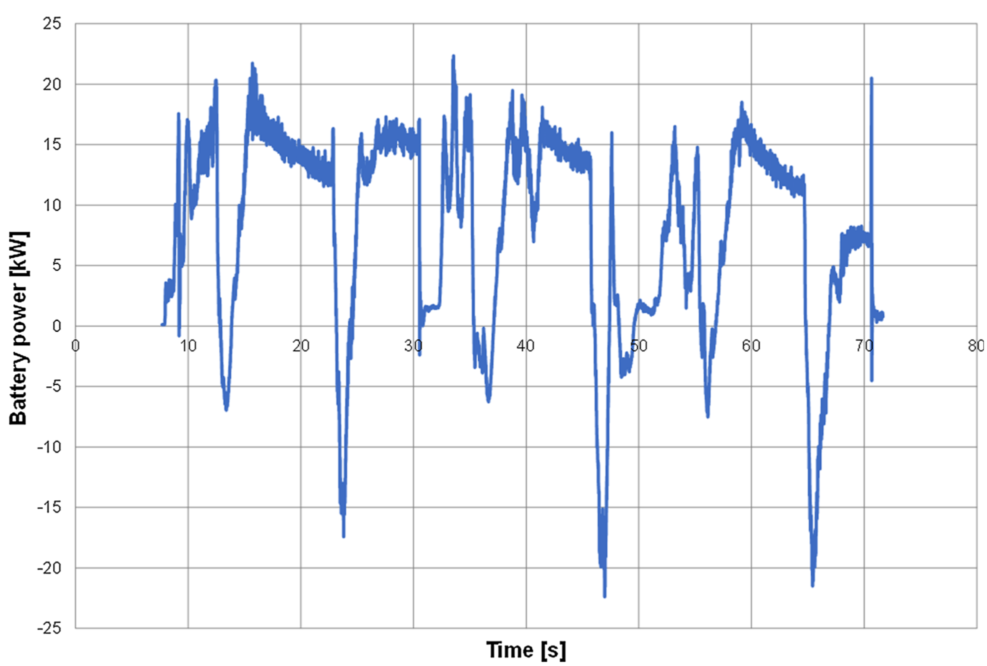


Fig. 2 The experimental battery power cycle in a typical mission of the electric forklift

where I^* is a reference current; $C_0 = C_0(I^*)$ is the battery capacity with the reference discharge current and at 0 °C. θ_f is the electrolyte freezing temperature; K_C, δ, and ε are empirical coefficients. This equation is more complex than Peukert's law, which has very high inaccuracy at low discharge currents [19].

Figure 3 reports the measured open circuit voltage and internal resistance measured.

The EC data used for the simulation are based on the Maxwell BMOD0165 module with a capacitance of 165 Farad. Table 3 summarizes the technical specifications of the EC module.

Figure 4 describes the electrical circuits [21] of the conventional configuration without EC (a) and of the modelled one (b) with the addition in parallel of an EC bank. In the configuration with the ECs, a DC/DC converter has been added to optimize the use of both storage devices: in this way the ECs can work with a higher voltage range, from the nominal voltage to half to be able to use 75 % of the stored energy. Further details about the DC/DC converter can be found in [21].

A dedicated control strategy, as described below, much simpler than those already developed and described in the literature [12, 16, 20–23], is introduced in the model to manage the operations of the EC module during forklift service:

- Discharge (power from storage system to the electrical motor): for low currents, the energy is taken from the battery, for higher currents from the ECs. The threshold value is dependent on the EC capacitance: so it is not initially fixed.
- Charge (regenerative braking): the energy flows to the EC, but, when $SOC_{EC} = 100$ %, the current flows into the battery.

The simulations are executed starting from a fully charged battery ($SOC_{BATT} = 100$ %) and stopped when SOC_{BATT} reached a value ≤ 20 %.

The experimental power profile is modified to take into account the presence of the EC and the minor power requirements on the lead-acid battery. Figure 5 shows the battery current profiles with and without EC, while Fig. 6 presents the corresponding voltage profiles.

Both Figs. 5 and 6 clearly show the evident effect of the EC on battery operations: the maximum battery current is reduced to about one-half (from more than 400–200 A), together with the absence of the negative currents flowing into the EC; while the battery voltage is levelled by the presence of the EC that limits the peak voltages.

Table 2 Specification of the battery used in the simulation

Tudor 5 h 445		
Current, A	Time, h	Capacity, Ah
115	5	575
395	1	395
640	0.5	320

Table 3 Specification of the EC used in the simulation

Rated capacitance	165 F
Rated voltage	48 V
Internal resistance	6.3 m Ohm
Maximum peak current	1,900 A

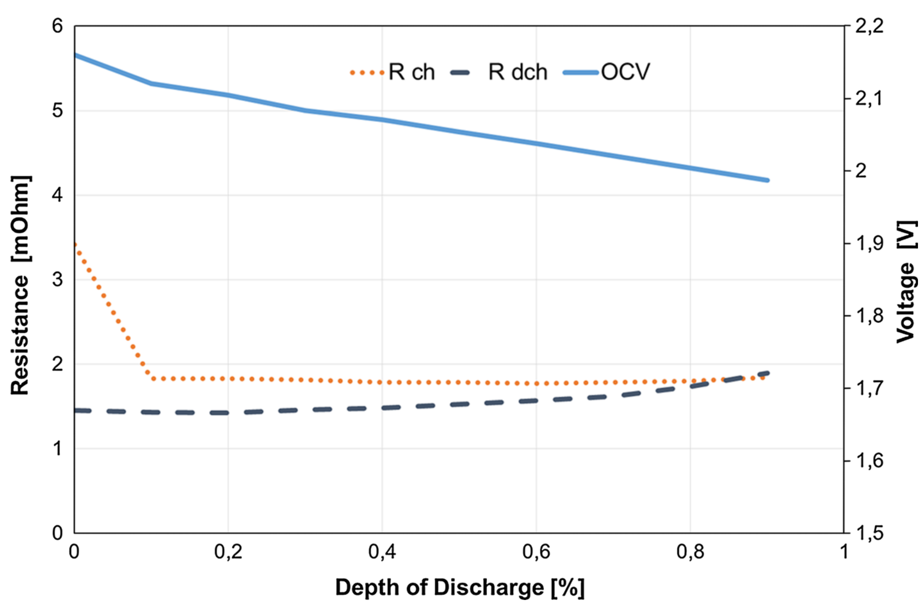


Fig. 3 Open circuit Voltage (OCV) and internal resistance (in charge and discharge) for the battery pack used in the simulation

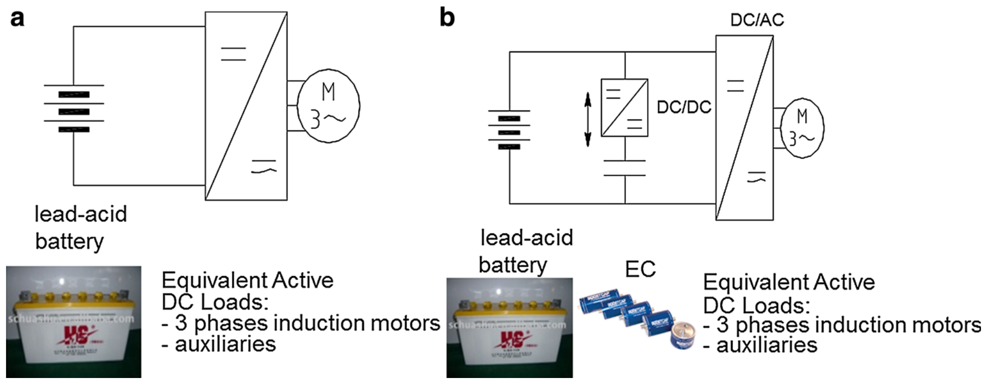


Fig. 4 Powertrain configurations (**a** without EC, and **b** with EC) developed in the model

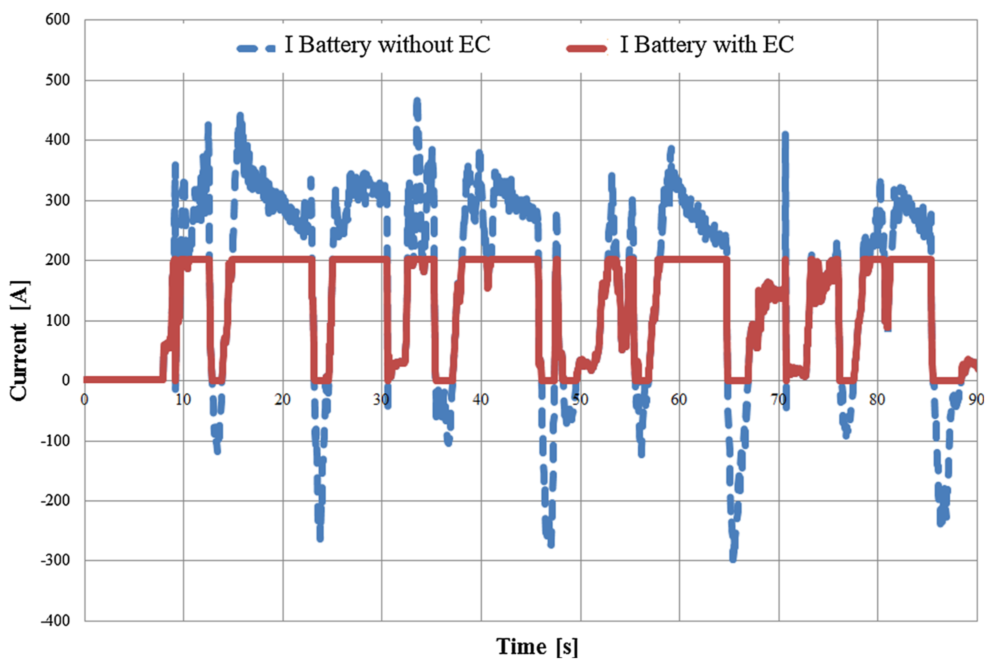


Fig. 5 Comparison of battery current profiles with and without the 165 F EC

Different EC sizes are simulated with capacitance ranging from 20 to 330 F.

Figures 7 and 8 illustrate two possible effects of hybridization with EC: the increase of overall forklift range and the reduction of the peak current required to the battery.

The simulation results well confirm substantial advantages and practical benefits associated with the addition of EC. For example, the extension of the forklift range is determined by more constant and minor current requirements from the battery and higher energy recovery from regenerative braking.

In Fig. 7 the range variation increases from 4 %, with the EC capacitance of only 20 F, to about 22 % with a 330 F capacitance. The benefits of the EC are then not negligible. The maximum current supplied by the battery decreases from 0.9 C, without EC, down to 0.23 C with an EC of 330 F, as shown in Fig. 8. Such improvements have also a positive impact on the battery life and operating costs, which have been verified with experimental activities.

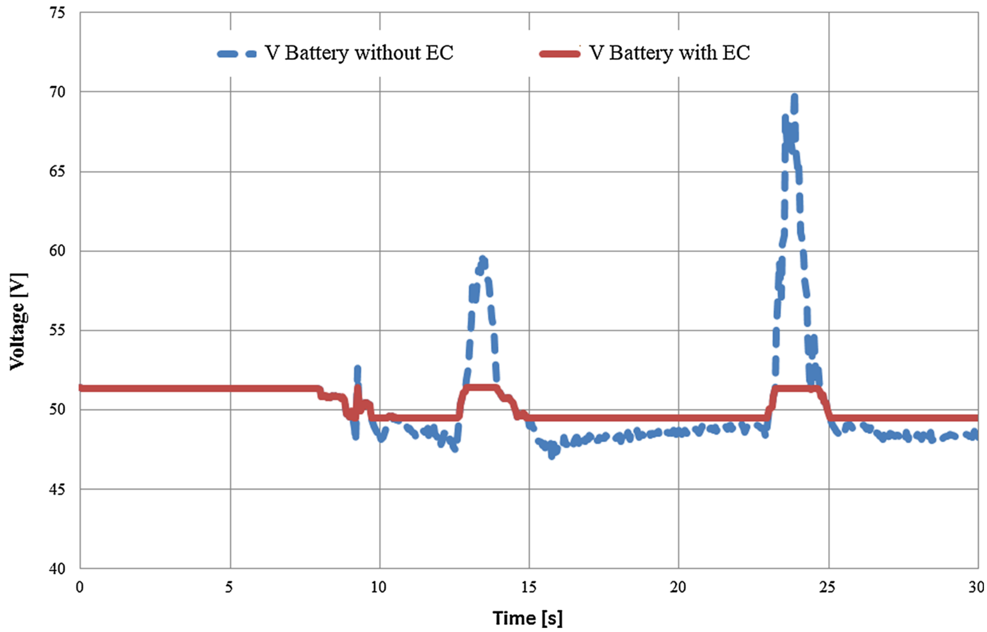
3 Input data and experimental results

A hybrid storage system is compared with a conventional one without EC in experimental laboratory tests. The scope of this activity is to validate the simulation results by focusing on the improvements of battery and vehicle performances due to the hybridization approach. Moreover, the final results of the test procedure and activities are aimed at determining the increase of the battery lifetime because of the beneficial assistance of the EC. These experimental results are also functional to the economical assessment of the proposed forklift modifications.

3.1 Test procedure

The tests are planned to evaluate the battery behaviour with different duty cycles. In addition to the power profile supplied by the forklift manufacturer, other driving cycles are used to have a more general investigation of the

Fig. 6 Comparison of battery voltage profiles with and without the 165 F EC



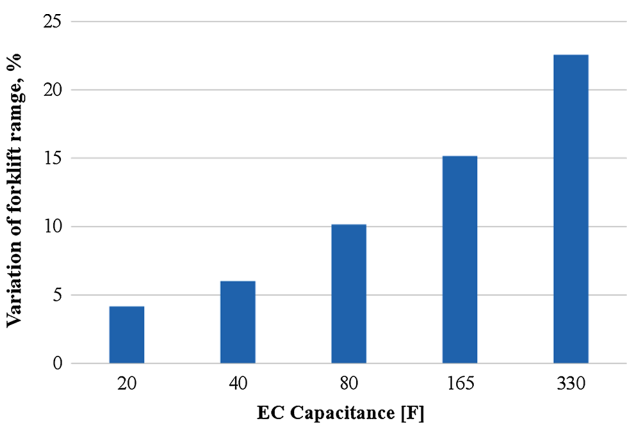


Fig. 7 Variation of forklift range with the increase of the EC capacitance

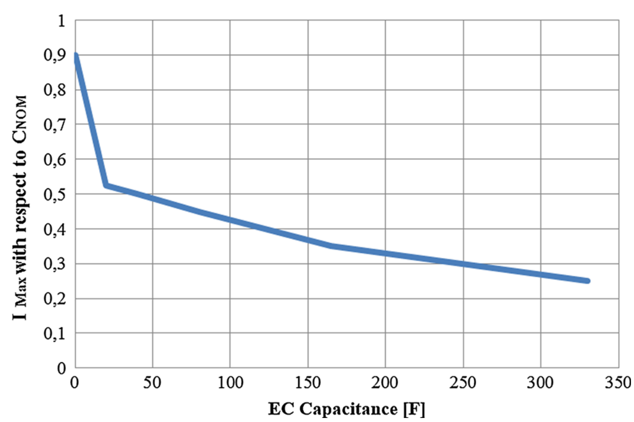


Fig. 8 Battery current reduction with the introduction of EC of different capacitances

possible impacts and benefits coming from the introduction of EC. For economic reasons, the experimental tests are carried out on various configurations of the hybrid storage systems, adequately scaled down with respect to the original size of the storage system, effectively used in the electric forklift. In this way, the execution of more tests allows for validation and assessment of a variety of applications.

For example, power profiles derived from international standards and testing procedures developed in various European projects are modified and adapted to different applications and vehicle designs.

As an example, in Fig. 9 a developed micro-cycle lasting 195 s is illustrated. A single test repeats a sequence of 25 micro-cycles and lasts 80 min. At the end of this test sequence the battery SOC_{BATT} is about 20 %, so that the battery has to be recharged before performing a new test. The resulting power profile for the battery is shown in Fig. 10, where the power contribution of the EC is detracted from the profile in Fig. 9. In this case, the regenerative braking energy is used to recharge the EC.

Figure 11 shows the testing equipment set up with samples under test in a dedicated Battery Test Facility, located at the ENEA Casaccia Research Centre. In this figure two storage systems composed of three series-connected lead-acid modules are tested: one of the two systems is in hybrid configuration with the addition of an EC.

Experimental data are directly recorded by the ELTRA battery cycler, and in parallel, by a Keithley data logger with a high sampling rate.

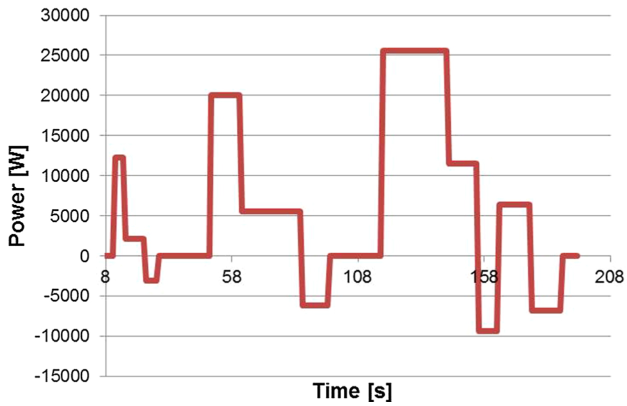


Fig. 9 A power micro-cycle lasting 195 s for the test without EC

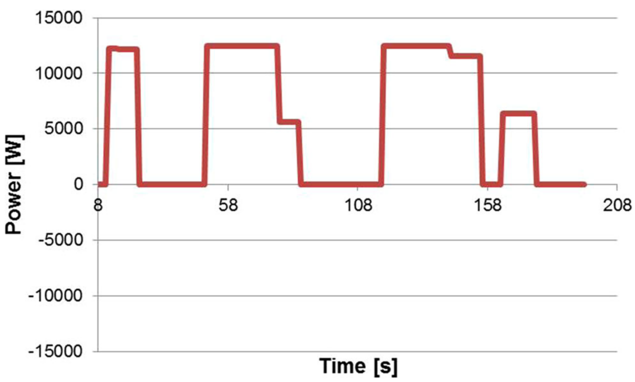


Fig. 10 Micro-cycle lasting 195 s of power supplied by the battery in hybrid configuration with EC

3.2 Experimental results

The analysis of experimental results during life cycling tests permits a direct comparison of the performance of two storage systems: one using only a lead-acid battery and the other in hybrid configuration with the addition of the EC. Figure 12 presents the power cycles for the battery, for the EC and for the entire hybrid system: in this case the EC bank has a capacitance of 165 F, the maximum required power is about 4.2 kW, and the achieved efficiency in charge/discharge for the EC is 97 %.

The results reported in Fig. 13 clearly demonstrate the effect of the integration of EC in the hybrid storage system, with a potential increase on the battery lifetime, as expected. It is evident that the battery capacity (in percentage over the nominal capacity, C_{NOM}) remains more stable with a reduced trend in degradation: after about 150 complete charge/discharge cycles, the battery in only battery configuration is fully degraded, while the battery in hybrid configuration is still cycling. In this case, it is estimated that the lead-acid battery cycle life in hybrid configuration may increase up to three-four times.

Fig. 11 Experimental set-up, with a battery cycler and two battery packs (three modules each) and EC

In fact, on the basis of the tests, it is possible to extrapolate the effect of the EC addition on the battery lifetime as function of the operative current peaks. As shown by the experimental curve depicted in Fig. 14, the estimated number of battery life cycles moves from point 1 to point 2, because of the reduction of battery maximum current from 500 to 200 A with the EC introduction: the battery cycle life is more than doubled.

This estimation curve can be expressed as a function of the maximum discharge current. The resulting exponential curve is the functional relationship that better fits, among various models, the experimental data [17, 18]. The achieved curve is described by means of the following equation:

$$L = a \cdot e^{-bI} \qquad (2)$$

where L is the battery lifetime, and I is the battery peak current. In (2), a and b are positive constants to be estimated by fitting the curves made with the experimental data.

4 Life-cycle cost assessment

The experimentally verified positive effects of the hybridization of storage system with the addition of the EC on the battery lifetime and the energy efficiency turn into a practical economical return. A direct life-cycle cost

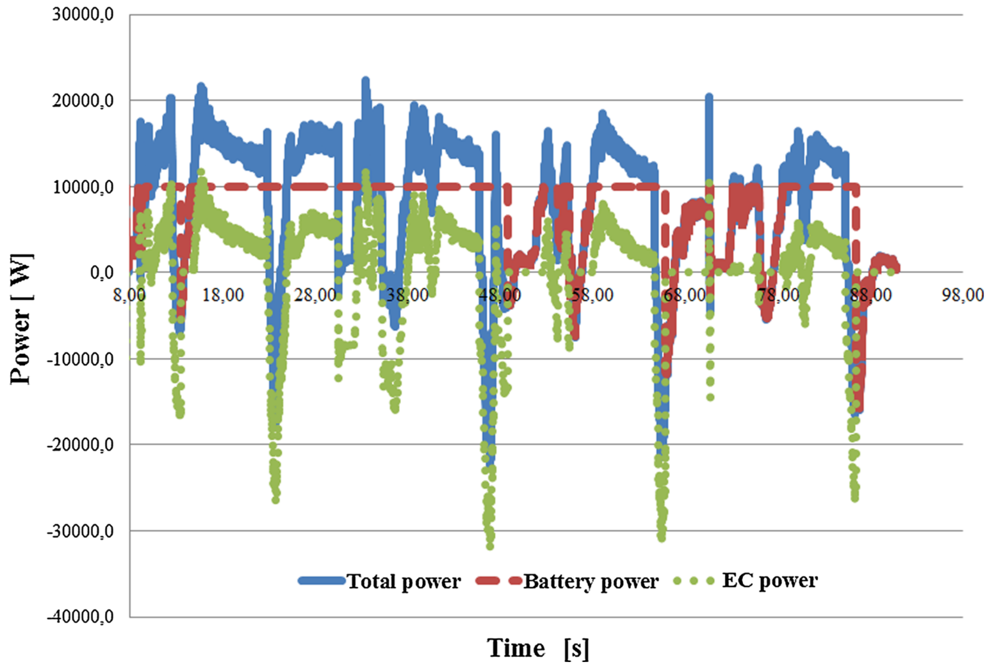


Fig. 12 Applied power cycles for the battery, for the EC and for the entire hybrid storage system

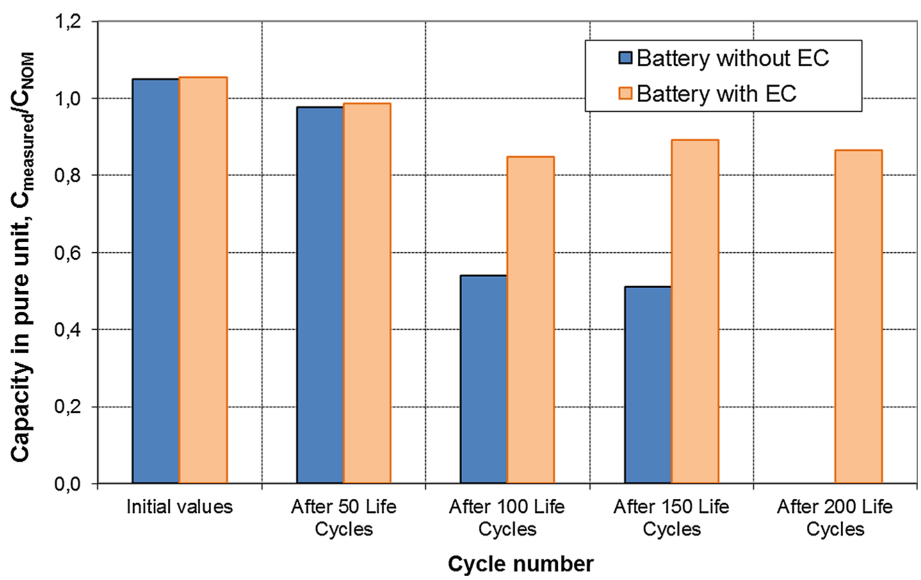


Fig. 13 Capacity (C/C_{NOM} at C/2 rate) of both battery packs (non-assisted by EC and assisted by EC) during life cycling

assessment takes into account not only the increase of battery lifetime and the improved energy efficiency, but also the additional cost needed for the modifications required by the forklift for the installation of the EC. Various parametric analyses are possible by comparing different working conditions, as partially reported in [22]. The reference costs of the key components are the following: 30 €/kWh (about 2 c€/F) for the EC, 100 €/kW for the DC/DC converter and 150 €/kWh for the lead-acid battery. The economical assessment considers also the number of battery and EC changes over the life of the electric forklift in both configurations.

Table 4 summarizes the life-cycle cost assessment results: the overall cost saving is estimated to be 30 %. The analysis considers the commercial costs of the main components, and the cost of modifications required with minor needs for possible battery substitutions during the life of the forklift.

5 Conclusions

The positive effects of the hybridization of the energy storage system with the addition of an EC for powering an

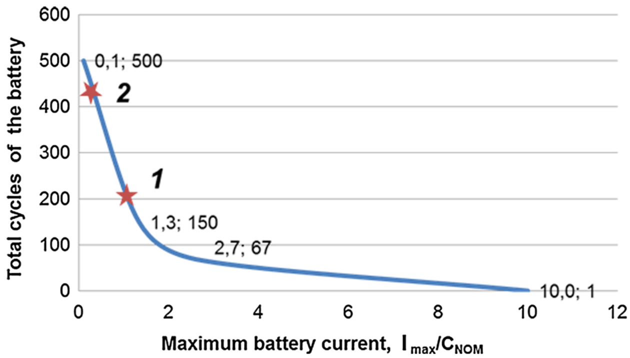


Fig. 14 Battery cycle life as a function of maximum current (I_{max} is the maximum current delivered by the battery with respect to the numerical value of the nominal capacity C_{NOM})

Table 4 Life-cycle cost assessment for the hybrid storage system

Configurations	EC and powertrain modification cost (in €)	Total battery cost at forklift end-of-life (in €)	Total cost of storage system (in €)	Life-cycle cost reduction with EC at end-of-life
Battery + 165 F EC	3,000	4,000	7,000	30 %
Only a 30 kWh lead-acid battery		10,000		

electric forklift are confirmed in this article by simulation, experimental results and life-cycle cost analysis.

The results discussed in this article on the use of ECs in energy storage systems with electrochemical batteries induce the following conclusions:

1. A careful analysis and design approach to optimize EC size and characteristics in the specific application is necessary to achieve a reliable and convenient hybridization of the storage system.
2. The lead-acid battery used in the forklift has undergone a much lower stress, as a consequence of the minor peak current requirement, which is shared with the EC.
3. The working time and the effective range travelled by the forklift are significantly improved by the EC addition, as resulting from the increased available energy associated to the longer cycle life of the battery (in the forklift case from 200 up to more than 400 cycles) and more efficient regenerative braking.
4. The exponential relationship between the battery life cycles and the peak current is confirmed and permits a direct estimation and an optimal design of the hybrid configuration, with significant life and cost reductions in experimental life cycle testing.
5. The life-cycle cost assessment demonstrates a clear economic advantage of the hybrid configuration with respect to the conventional one, whenever correct design and proper modifications are accomplished.

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